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COLLEGE OF ENGINEERING
NAVAL ARCHITECTURE AND OFFSHORE ENGINEERING

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Decmeber 27, 1991

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Final Technical Letter for ONR Contract N00014-88-K0629
UCB # Z25810
Contract title: Wave Viscosity Interaction in Nonlinear Roll Motion

Dear Jim:

Described herein is a summary of the highlights and significance of the research resulted from the above contract. In Section 1, a description of thematic areas at issue is reviewed. In Section 2, a complete list of the technical papers or reports that have been supported in part or in full during the 3-year contract period is provided.

1. Technical Objectives & Significant Accomplishments

The objective of the our research program is to develop rationally-based hydrodynamic models for describing and analyzing viscous flows about ship sections, particularly, in the context of nonlinear roll motion of ships, where viscous damping is known to be important. These objectives were primarily met by conducting research along the following thematic areas:

1.1 Grid-generation mathematics for free-surface flows

This research consists of developing the necessary grid-generation mathematics for finite-difference methods that would enable the researcher to handle skewed geometries in steep water waves. The success of this phase is essential to the work in thematic area §1.4 below. The capabilities accomplished is documented in the following technical papers: Ref. [1], [2], and [9]. Specifically, an innovative technique using a variational formulation together with a reference space was initially demonstrated by solving a number of nonlinear inviscid-fluid problems involving large-amplitude waves (ref. [9]) .

1.2 Hydrodynamic resonance in a closed domains and towing tanks

As we progressed along the research lines described in this section, it became apparent that some fundamental understanding of the resonant behavior of the

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fluid in a tank with the presence of floating bodies was indispensable. This is related to the fact that any eventual validation of the theoretical models developed in this research program would require tank testing. The hydrodynamic properties of bodies in a finite-width tank was a subject not well treated. Four technical papers on the issue of resonance in a closed domain, as well as resonance in the case of towing tank were completed in the course of this research (Ref. [2], [3], [4], [5]). Th major findings consist of 1) a time-dependent Fourier technique to determine the resonance modes, and 2) the properties of the singular behavior of the hydrodynamic coefficients near the resonant frequencies in a towing tank. More details may be found in these publications.

1.3 Time-harmonic oscillating body in a viscous fluid

The major focus of this activity is on the development of an analytical formulation that would allow one to incorporate the effects of viscosity in a framework that can be unified with the formulation of existing, traditional ship-motion theories, thus facilitating eventual practical applications. This research has led to a new theory for calculating added mass and damping of two-dimensional sections in a viscous fluid. Under the appropriate assumptions, we were able to linearize the Navier Stokes Equations to obtain a problem, in which the precise effects of viscosity appear as a frequency-based Reynolds number. This problem was solved analytically and numerically. The research findings constitute the Ph.D. dissertation of C-F. Wu (Ref. [6]) and the corresponding results were published in two papers (Ref. [7], and [8]), with the second work in press at the time of this report.

1.4 Highly-separated flows about blunt bodies

Since the middle of the second contract year, it was decided that the above studies was complemented by another project that would examine the behavior of fully nonlinear separated flow based on a *grid-independent* method. The highlights of some of our recent accomplishment by using a Random Vortex Method (RVM) were given on a graphics sheet submitted with the October, 1991 EOFY-letter report. Although no publications have resulted from this particular study at this time, the research is leading to two major documentations (one publication and one departmental report) in the forthcoming year.

Along a path parallel to the above, the approach of §3.1 has been pursed with the complex effects of viscosity included. Some preliminary indications of the success of this approach are reflected in the conference paper Ref [10]. The viscous-flow problem with a free surface and floating bodies can be successfully solved using a primitive-variable formulation and a "projection method". This topic of research has been generalized and extended in a paper to be published in the upcoming silver anniversary issue of the *Journal of Engineering Mathematics*.

Research along both lines is being continued in a follow-up grant.

2. List of Publications & Reports (derived from the research program)

[1]** Yeung, R. W. & Ananthakrishnan, P.,"Nonlinear Solution of Nonlinear Wave and Wave Body Interaction Problems using a New Method of Boundary-fitted Coordinates", in *Proceedings*, 4th Int'l Workshop on Water Waves & Floating Bodies, May 2-8, 1989, Oystese, Norway.

[2]** Yeung, R. W. & Wu, C-F., "Nonlinear Wave-Body Motions in a Closed Domain", *Computers & Fluids*, **17**, no. 2, 351-370, 1989.

[3]** Yeung, R. W. & Wu, C. F., "Über nichtlinere Wellenbewegung in einem geschlossenen Gebiet", *Jahrbuch der Schiffbautechnishen Gesellschaft*, 83 Band, pp. 29-41, 1989.

[4]** Yeung, R. W. & Sphaier, S. H., "Wave-interference effects on a truncated cylinder in a channel", *J. Engineering Mathematics*, **23**, 95-117, 1989.

[5]** Yeung , R. W. & Sphaier, S. H., "Wave-Interference Effects on a Floating Body in a Towing Tank", *Proceedings*, 4th Int'l Symp. on Pract. Design of Ships & Mobile Units, Varna, Bulgaria, Paper 95, October, 1989.

[6] Wu, C.-F., "Wave-Viscosity Interaction for Bodies in a Free Surface", Ph.D. dissertation, Dept. of Naval Architecture & Offshore Engineering, University of California, Berkeley, June, 1990.

[7]** Yeung, R. W. & Wu, C.-F., "Viscosity Effects on the Radiation Hydrodynamics of Two-dimensional Cylinders", *Proceedings*, 10th Conf. Offsh. Mech. & Arctic Engrg., Stavanger, Norway, June 1991.

[8] Yeung, R. W. & Wu, C. F. "Viscosity Effects on the Radiation Hydrodynamics of Horizontal Cylinders", *Journal of Offsh. Mech. & Arctic Engrg.*, ASME Publisher, to appear, December 1991.

[9]** Yeung, R. W. & Vaidhyanathan, M., "Nonlinear Wave Diffraction over Submerged Obstacles", *Proceedings*, 5th Int'l Workshop on Water Waves & Floating Bodies, Manchester, England, March, 1990.

[10]** Yeung, R. W. & Ananthakrishnan, P., "Large-Amplitude Oscillation of Two-dimensional bodies in a Viscous Fluid with a Free Surface", *Proceedings*, 6th Int. Workshop on Water Waves & Floating Bodies, Woods Hole, Mass, April, 1991.

Asterisked items in Section 2 are enclosed herewith this final letter. A copy of Ref. [6] has already been sent to your office earlier for your file. Please advise me if you need additional copies.

On behalf of all research students, visiting scholars, and other participants of this research program, I would like to express here our sincere thanks to ONR for the support in these pioneering efforts and your personal administrative assistance in many aspects.

Submitted by

Professor Ronald W. Yeung
Principal Investigator

cc:
ORS (Suzanne Kempton)
SPO (Pat Gates)
ONR Res. Rep (Linden Clausen)

Encl:
Reprints for 8 articles.

Abstract for the 4th International Workshop on Water Waves and Floating Bodies, Oystese, Norway, 1989.

Solution of Nonlinear Water-Wave and Wave-Body Interaction Problems using a new Boundary-Fitted Coordinates Method

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In this paper, nonlinear time-dependent water-wave and wave-body interaction problems are studied using a finite difference formulation based on a new method of coordinates generation. Although the use of boundary integral methods is more economical and less time-consuming, for two-dimensional potential flow simulations, the finite difference method can provide a natural framework for solving unsteady viscous flow problems that are of importance in a number of naval and offshore engineering applications. In field discretization procedures such as the finite difference method, the accuracy of the solution depends on the implementation of the boundary conditions as well as on the properties of the mesh system. Generation of grids by the method of boundary-fitted curvilinear coordinates, with the extreme coordinates conforming to the boundaries, is an efficient means of discretizing a physical domain and implementing the boundary conditions. According to this method, the physical domain is mapped onto a computational domain which is usually uniform and rectangular. The governing equations and boundary conditions are also transformed and then solved in the computational space. An overview of some of the applications may be found in Yeung [1] and Thompson et al. [2]. Among the various grid-generation methods, the one introduced by Thompson et al. [3] which uses a set of Poisson equations to describe the transformations, has been quite popular in free-surface hydrodynamics (see e.g. Coleman and Haussling [4], Telste [5], Yeung and Wu [6]). However, this method is also known to cause problems such as grid-skewness and foldings when the free surface becomes steep or multivalued. In an attempt to overcome these problems, Ghia et al. [7] and Coleman and Haussling [4] suggested certain special treatments within the framework of the Thompson's method. They were able to model steep waves with limited success, but were unsuccessful in modelling overturning waves. Others like Miyata [8] resorted to the use of Lagrangian segments together with "irregular-stars" to track the free surface. Simulation of overturning waves was possible but there were inherent difficulties in applying such a scheme to flows where strong gradients exist in certain local regions.

In the present work, the grids that discretize the physical domain are generated using a variational formulation (see for e.g. Brackbill and Saltzman [9]) along with the notion of an intermediate reference space. The field equations for the grid-generation problem are derived as a product transformation of the physical space onto the computational space via a reference space. Results presented here show that our method can indeed cope with steep and overturning waves. Fig. 1 illustrates the transformations involved in this grid-generation procedure. In order to demonstrate its capability to treat highly nonlinear waves and wave-body interactions, two case studies are presented. In the first case, the overturning and breaking of a large-amplitude shallow-water wave are examined. The second case corresponds to the nonlinear flow about a slightly submerged cylinder. Both cases are tackled using a mixed Eulerian-Lagrangian formulation [10] with a finite-difference technique similar to [6]. Work-energy balance is used to monitor the accuracy and stability of the finite difference scheme.

For the first problem reported here, the solutions based on linear theory are used as initial conditions to start the calculations in shallow water. Periodicity conditions are

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NONLINEAR WAVE-BODY MOTION IN A CLOSED DOMAIN

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(Received 8 February 1988; in revised form 20 July 1988)

Abstract—A finite-difference method based on boundary-fitted coordinates is combined with a Lagrangian description of the free surface to solve the nonlinear fluid-motion problem in a tank. Numerical results are obtained for the impulsive response of a tank and the forced heaving (vertical) motion of a body in a tank, for both linear and nonlinear problems. Long-time solutions are found to have excellent stability characteristics and fine convergence properties.

1. INTRODUCTION

In the last decade, there have been considerable research activities devoted to nonlinear free-surface problems. An overview of the methods for tackling them may be found in Yeung [1]. The mixed Eulerian–Lagrangian formulation developed by Longuet-Higgins and Cokelet [2] provides an approach that is particularly effective in simulating large-amplitude free-surface motions. By assuming periodicity in space, they were able to simulate steep Stoke's waves, as well as wave breaking. Their integral-equation method was later extended to incorporate the presence of a floating body by Vinje and Brevig [3] and Lin *et al.* [4]. Other variants of the integral-equation formulation have also been successfully employed by Baker *et al.* [5] and Dold and Peregrine [6]. In addition, a finite-difference method was also combined with the mixed Eulerian–Lagrangian formulation by Telste [7] to study a nonlinear free-surface problem.

In the present paper, a finite-difference method is developed to study time-dependent nonlinear free-surface flows with particular attention directed to the effects of a closed domain. Other works in a closed domain consist primarily of studies of sloshing phenomena [8–10]. Estimations of natural frequencies of a basin based on linear shallow-water theory have been given by Evans and McIver [11] and McIver and Smith [12]. Our present approach has two important features: (a) the automatic grid generation and (b) the mixed Eulerian–Lagrangian formulation of the free surface. Numerically-generated boundary-fitted coordinates [13] have the advantage of being able to satisfy boundary conditions such as those on a floating body more precisely. A Lagrangian description of the free surface facilitates easy tracking of the position and potential of the free surface particles. Miner *et al.* [14], for instance, have used a direct Lagrangian approach for the entire fluid domain.

Two test studies of this numerical method are reported here: the response of a tank due to the impulsive motion of a boundary and the response due to oscillatory heaving motion of a cylinder with vertical sides. The heaving motion of a cylinder with vertical sides is chosen because theoretical analysis reveals that this particular case contains no singularity at the body and free-surface intersection [15]. Energy checks indicate that the method is very stable and accurate. No smoothing of the free-surface profile, as reported in some of the earlier methods, is needed.

2. GOVERNING EQUATIONS FOR FLUID MOTION IN A CLOSED DOMAIN

The fluid motion in a 2-D symmetric tank with a symmetric body is considered. The x-axis is placed on the undisturbed free surface and the y-axis on the axis of symmetry, pointing upwards (Fig. 1). Only the right half of the flow field needs to be modeled since the flow is symmetric with respect to y-axis despite the nonlinear boundary conditions stated below. All variables have been nondimensionalized by the primary variables $\bar{\rho}$ (fluid density), $\bar{g}$ (acceleration of gravity), $\bar{b}$ (body

On Nonlinear Wave Motion in a Closed Domain

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Über nichtlineare Wellenbewegung in einem geschlossenen Gebiet

On Nonlinear Wave Motion in a Closed Domain

Summary. Fully nonlinear motion of an inviscid fluid in a closed basin is simulated using a boundary-fitted coordinate method. A mixed Eulerian-Lagrangian formulation is used. An analysis of the singular behavior of the velocity at the intersection of the free surface and the basin boundary is also given. It reveals that the velocity is bounded for a "beach-like" intersection. Natural frequencies for several basin geometries are obtained and compared with existing estimates. The numerical method is effective and remains stable up to the time breakers start to develop on the boundary slopes.

Dedication

Prof. Wieghardt's outstanding contributions in education and research have been enumerated on many occasions. In this gathering held in his honor, I thought I would, instead, reminisce my first encounter with him. It was in 1974, at the 10th ONR Symposium at Cambridge, Massachusetts, that my colleague K. J. Bai and I made our first major presentation. I remember well that Prof. Wieghardt was the chairman of our session, although this may not be recorded in the Proceedings. Were it not for his role as a perfect chairman, we, as newcomers to the field, would have been overawed by the sheer number (7, a record at the time?) and reputation of the discussers of our paper. He had kindly collected for us most of the discussions hours beforehand, thus removing many worries from our minds. There were some surprises, but our presentation and discussion went smoothly. It took me only a couple more conferences to realize that it was a very kind gesture that he had bestowed upon us that afternoon. Our paths have crossed just twice since then. But to this day, I am still grateful to him for having defined the "boundary conditions" in such a way that my career did not start with a negative slope! Prof. Wieghardt, I am most pleased to be able to participate in this event at your home institute today. It is a pleasure to dedicate this work to you and if I may, I would also like to offer a belated "Vielen Dank und alles Gute zum Geburtstag".
(R. W. Yeung, January 6, 1989)

1 Introduction

The problem of nonlinear motion of an inviscid fluid in a two-dimensional closed domain or basin is examined. This fully nonlinear unsteady problem is formulated in a mixed Eulerian-Lagrangian form [1]. The fluid boundaries can be either stationary or moving. In the latter case, the boundary can be used as a device to excite the motion of the fluid. An impulsive excitation generates a large number of natural modes, thus providing much information on the resonant frequencies of the basin. The problem being investigated is therefore also closely related to studies of sloshing motion of water in tanks which have received much attention in the past [2-7]. The present paper addresses a number of aspects that are particularly essential for obtaining accurate and reliable nonlinear numerical solutions. In the first part of the paper, we point out that a change in the boundary geometry, such as that associated with a wavemaker paddle, results in a new static term in the unsteady Euler's integral. This term is associated with the change in the static potential energy of the fluid because of a change in the configuration of the fluid system. The usual relations for a laterally unbounded fluid remain applicable if a properly modified static pressure component is introduced.

An important feature of the Eulerian-Lagrangian formulation consists of tracking the evolution of the free-surface particles. Difficulties exist in advancing the numerical solution if such free-surface velocities become infinite. Problematic situations have been observed at the intersection of a rigid boundary and the free-surface [8]. The second part of the paper provides an analysis of the singular behavior caused by the confluence of the boundary conditions at such intersection points. It is shown that the behavior of the fluid velocity depends on the intersection angle and the homogeneity of the Neumann condition on the rigid boundary. In

Journal of Engineering Mathematics 23: 95-117, 1989.

Wave-interference effects on a truncated cylinder in a channel

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Received 21 September 1988; accepted 7 December 1988

Abstract. The effects of channel walls on the hydrodynamic properties of a floating vertical cylinder are examined. An interior eigensolution under the cylinder is matched with an exterior eigensolution in a manner similar to Yeung [1]. Wave effects due to an image cylinder can be conveniently expressed in terms of the coordinates of the central cylinder by the use of Graff's theorem. The infinite array results in a slowly convergent series which has to be summed with caution. Results for the heave added mass and damping of a cylinder for several geometric configurations are obtained. Also presented in the paper are results for the diffraction of incident waves about the same cylinder. The channel walls exert an important influence on the radiation and diffraction properties, the latter to a lesser extent. Such influence is characterized by the presence of "spikes" at wave frequencies corresponding to the occurrence of symmetric transverse resonant modes in the channel. An analytical solution of a three-dimensional flapper wavemaker given in the Appendix further confirms such characteristics. In the high-frequency range, the radiation properties approach those of a single cylinder. In the low-frequency limit, they exhibit a behavior similar to that of a two-dimensional horizontal cylinder heaving in water of finite depth.

1. Introduction

The evaluation of hydrodynamic coefficients for bodies oscillating near a free surface plays an important role in the study of their behavior in the sea. More recently, there has been an increase of interest in studying hydrodynamic interference effects among bodies [2, 3, 4]. Such interests stem from the fact that many offshore structures or wave-energy extractors are made of a collection of identical geometrical components. Interference effects are also of practical concern when excessively large models are tested in wave tanks of relatively limited width [5]. Finally, in performing numerical computations, it is not unusual to simulate laterally unbounded flow by truncating the fluid domain with channel walls [6]. Some theoretical understanding of the hydrodynamic interference caused by imaging effects of the channel walls is thus highly desirable.

This paper examines the hydrodynamic characteristics of a single body placed in an *infinite* array of its own images. For simplicity, we have chosen to study a vertical (floating) cylinder of finite draft. Its radiation properties for heaving motion are obtained as a function of frequency and the relevant geometric parameters. Also solved here is the complementary problem of wave diffraction about this cylinder in an array configuration. This particular body geometry for the case of *laterally unbounded water* was solved by Garrett [7] for wave diffraction and by Yeung [1] for wave radiation. The method of matched eigenfunction expansions used therein reduced the problem to the numerical solution of an infinite system. Such a quasi-analytical treatment has been used subsequently with success by Miao and Liu [8], McIver [9] and Kagemoto and Yue [10] in a variety of related contexts. The present

Paper presented at *PRADs '89*, Varna, Bulgaria, October 23-28, 1989.
Proceedings, PRADSs '89, vol. 3, pp. 95.1 - 95.13

WAVE-INTERFERENCE EFFECTS ON A FLOATING BODY IN A TOWING TANK

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ABSTRACT

Hydrodynamic-force coefficients for a vertical cylinder in the presence of tank walls are presented for heave, surge, pitch, roll, and sway. Also shown are the corresponding results for wave-exciting forces and free-body motions. The matched eigenseries method of [1, 2] is used to obtain the solutions of the problems. Numerical results indicate that the hydrodynamic characteristics of the cylinder can be severely altered by the occurrence of transverse resonant modes of the tank. Added mass and damping of heave, sway and roll, and the vertical wave-exciting force are particularly vulnerable. In the neighborhood of these resonant frequencies, a "spiky" behavior occurs. Longitudinal motions along the tank, such as surge and pitch, and wave exciting forces associated with these motion are much less affected. It is also pointed out that the low-frequency limits of the heave added-mass and damping in the presence of tank walls are drastically different from those of unlimited tank width.

1. INTRODUCTION

Offshore activities searching for oil and other energy resources from the sea have stimulated the design of many different kinds of structures. To study the behavior of such structures in waves, it is important to have a precise knowledge of their hydrodynamic characteristics. A common practice is to conduct scale-model tests in a wave tank. Because of physical limitations on tank width, laboratory tests can suffer from interference effects arising from the presence of the tank walls. This situation is particularly critical when long-time responses such as those associated with slow-drift motion is measured. The purpose of this paper is to examine from a theoretical viewpoint how tank-wall interference may come into play and to present an assessment of how such interferences may affect the overall response of the body in the context of linear theory.

In order to make the problem at hand more manageable in scope, we shall consider a body of relatively simple geometry: a floating vertical cylinder. However, it is expected that the general conclusions arrived at here remain applicable to more complex body geometry. Specifically, we will develop the solution of the radiation and diffraction problems for a cylinder located at the centerline of a towing tank. The solution procedure used here is similar to the one adopted earlier by Yeung [1], in which eigenfunction expansions under and outside of the cylinder are properly matched at a hypothetical cylindrical interface. This semi-analytical procedure leads to a linear system of algebraic equations for the coefficients of the series. In the present problem, the infinite array of cylinder images caused by the tank walls introduces two complexities. First, the imaging effects results in a slowly convergent series which need to be treated with caution. Second, the absence of axisymmetries gives rise to a coupling between the circumferential and vertical modes of the expansion. These difficulties have been successfully tackled by Yeung & Sphaier [2]. In this recent work, aside from presenting solutions of the heave radiation problem and the wave-exciting forces, the authors have also provided an explanation for the presence of the "spikes" in typical hydrodynamic results. This "spiky" behavior occurs near a set of "cut-off frequencies", which correspond to the occurrence of resonant transverse standing waves in the tank in the absence of the body.

The present work extends the basic theory of [2] to include sway, roll, surge and pitch motions of the cylinders. As will be shown, tank-wall effects on the latter two modes are of a weaker type when compared with the other cases. To complete the overall hydrodynamic analysis, we also present results of the heaving motion and the coupled surge and pitch motion of a freely floating cylinder. These are compared with the corresponding results for an open sea. Situations where severe interference effects can occur are pointed out. There exists only a limited amount of literature on tank-wall effects [3-7]. A closely related problem is one involving the treatment of interferences among a finite number of bodies [8-13]. The present study, therefore, aims at providing a baseline evaluation of the influence of tank

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VISCOSITY EFFECTS ON THE RADIATION HYDRODYNAMICS OF TWO-DIMENSIONAL CYLINDERS

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Abstract

The problem of a body oscillating in a viscous fluid with a free surface is examined . The Navier Stokes equations and boundary conditions are linearized using the assumption of small body-motion to wavelength ratio. Generation and diffusion of vorticity, but not its convection, are accounted for. Rotational and irrotational Green functions for a divergent and a vorticity source are presented, with the effects of viscosity represented by a frequency Reynold number $R_\sigma = \bar{g}^2/\bar{\nu}\bar{\sigma}^3$. Numerical solutions for a pair of coupled integral equations are obtained for flows about a submerged cylinder, circular or square. Viscosity-modified added-mass and damping coefficients are developed as functions of frequency. It is found that as R_σ approaches infinity, inviscid-fluid results can be recovered. However, viscous effects are important in the low-frequency range, particularly when R_σ is smaller than $O(10^4)$.

Nomenclature

$\bar{a}$	Characteristic dimension of cylinder
$\bar{a}_x, \bar{a}_y$	Horizontal and vertical displacement of O'
F_x, F_y	Horizontal and vertical forces per unit density$/(\bar{g}^2\bar{\sigma}^{-2}\bar{a}_y)$
G_1	Divergent source function, potential component
G_2	Divergent source function, stream-function component
G_3	Vorticity source function, potential component
G_4	Vorticity source function stream-function component
H_1	Regular part of G_1
H_4	Regular part of G_4
M	Moment about body origin O'
$\mathbf{n}$	Unit normal pointing into body, $= (n_x, n_y)$
N	Number of segments of body contour
Oxy	Inertial coordinates fixed on earth
$O'x'y'$	Body-fixed coordinates
p	Field point $(x\ y)$
p_d	Hydrodynamic fluid presure
P_{ij}, Q_{ij}	Normal-velocity influence coefficients
q	Source point (ξ, η)
r	Distance between source point and field point
R_{ij}, S_{ij}	Tangential-velocity influence coefficients
R_σ	Frequency Reynold's number $\equiv \bar{g}^2/\bar{\nu}\bar{\sigma}^3$
(u, v)	Velocity of fluid particles
α	Wave number, normalized by $\bar{\sigma}^2/\bar{g}$
$\gamma(t)$	Roll angle of body about O'
γ_0	Roll amplitude
δ_{ij}	Kroenecker delta
ϵ	Viscosity parameter $= 1/\sqrt{R_\sigma} = \sqrt{\bar{\nu}\bar{\sigma}^3}/\bar{g}$
μ_{ij}, λ_{ij}	Added mass and damping coefficient in i-th direction due to body motion in the j-th direction
$\bar{\nu}$	Kinematic viscosity coefficient of fluid
$\bar{\sigma}$	Angular frequency of oscillation
σ_ϕ	Distributed strength of divergent source
σ_ψ	Distributed strength of vorticity source
ϕ_1	First-order velocity potential (irrotational)
ψ_1	First-order stream-function (rotational)
χ	Small-motion parameter, $\bar{\sigma}^2\bar{a}_y/\bar{g}$
Ω	Frequency parameter, $\bar{\sigma}^2\bar{a}/\bar{g}$
$\bar{\ }$	Dimensional quantities
(m)	Index for motion mode, superscript

1. Introduction

The hydrodynamic theory of bodies oscillating near a free surface has been important in the calculation of wave forces on offshore structures as well as in the prediction of their motions. Classical treatment of this subject in the framework of potential-flow theory may be found in Wehausen (1971). Numerical and other relevant aspects have also been addressed by Yeung (1982). Although this body of literature is extensive, it appears that relatively little attention has been devoted towards a systematic examination of the effects of viscosity.

A conventional way of accounting for viscosity is through the use of Morison's equation (Morison et al., 1950), whereby the effects of fluid acceleration and of viscous form drag are modeled by introducing two empirically determined coefficients. The basis of this approximation appears well justified in an infinite fluid. In the presence of a free surface, however, the validity of such an approach has not been established from fundamental principles. Since there are two coefficients that can be "juggled" to achieve the necessary good "fit" with the force history, issues concerning validity of the Morison form of representation often become obscure.

A somewhat different starting point for modeling viscous effects is to formulate the complete nonlinear fluid-mechanics problem. In fact, direct solutions of the Navier Stokes equations have already been sought with only a minimal number of assumptions. The works of Miyata *et al.* (1987), Hino (1987), Tiemroth (1986) and Stansby

Extended Abstract, *The Fifth International Workshop on Water Waves and Floating Bodies*, Manchester, England, 25-28 March, 1990.

Nonlinear Wave Diffraction over Submerged Obstacles

by

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Introduction

Recently there has been considerable interest in simulation of nonlinear waves diffracting over submerged obstacles. For bodies which are shallowly submerged, strong nonlinear behaviour is observed in the immediate vicinity of the body. Another characteristic is the generation of higher harmonics in the reflected and transmitted waves [1]. A sizeable number of past investigations have been devoted to interactions of solitary waves with bottom topography, e.g. [2]. Our present work focuses more on the effects of periodic incident waves; specifically, our goals include the determination of the magnitude of the shorter waves, the calculation of the forces and simulation of wave breaking, should that occur.

In the last workshop, a finite difference scheme using a new boundary-fitted coordinate method was discussed [3]. Using this particular technique, which is well suited for solving problems with boundaries of complex geometry, such as those that appear in nonlinear free-surface flows, we simulate, in time domain, flows over submerged bodies. Two different geometries are presently being studied - i) a submerged circular cylinder and ii) a bottom mounted semi-circular cylinder (sandbar).

Numerical Procedure

The model we are using consists of a rectangular wave tank, with a piston type wavemaker at the left end. The wavemaker generates sinusoidal waves which in turn interact with the submerged body. The water is initially is taken to be at rest. The amplitudes of the wave components upstream and downstream are computed using the Fast Fourier transform technique.

Since the mixed Eulerian-Lagrangian formulation [5] is used to advance the free-surface, even breaking waves can be simulated using the particular grid generation scheme of [3].

Typically nondimensionalization is carried out with the radius of the body and the acceleration due to gravity being set to 1. Simulation is carried on for 4 to 8 periods, which takes about 400 time steps. This is long enough for the diffracted waves to appear. The body is placed at a distance of at least 1 to 2 wavelengths away from the wavemaker. This is especially important for the second case, where standing wave modes between the wavemaker and the cylinder could be excited. For the submerged cylinder, the cases being studied correspond to the ones for which experimental data are available [4].

Results and Discussions

In Fig 1., the velocity vector plot for the case of flow over a submerged cylinder after 8 periods is shown. The wavelength (λ) and submergence of the center of the cylinder (h), non-dimensionalized with respect to the radius of the cylinder (a) are 7.45 and 1.5 respectively. This corresponds to a ka of 0.84, where k is the wave number. Fig 2. and Fig. 3 show the time evolution of the free surface elevation

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LARGE-AMPLITUDE OSCILLATION OF TWO-DIMENSIONAL BODIES IN A VISCOUS FLUID WITH A FREE SURFACE

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Nonlinear flow due to forced sinusoidal heaving of a surface-piercing cylinder is analysed. This problem is of importance in the design and in the motion response of various floating structures which experience significant nonlinear wave and vortex-induced forces.

Field equations governing this problem are the incompressible Navier-Stokes equations. Free-surface conditions, determined by kinematic and stress-continuity relations, can be found in [1]. On the solid body the no-slip condition is to be satisfied. Approximate conditions are used at the contact points (intersection of free surface and body boundary) and on the open boundary. At the contact points, the tangential component of the velocity on the body is obtained assuming the shear stress to be zero. Pressure at the open boundary is assumed to be that of the static case for finite duration of time. Initial conditions correspond to a velocity field and free-surface elevation both of zero value.

Solutions to the fully nonlinear problem are obtained using a primitive-variables based finite-difference method. The *projection* formulation developed in [2] is used for advancing the solution in time. According to this formulation, an auxiliary velocity field, which does not satisfy the equation of continuity, is first computed. The auxiliary field is then projected onto the divergent-free velocity and curl-free pressure-gradient fields. This method is extended in [3] for solving viscous free-surface flow problems in curvilinear coordinates. A grid-generation procedure based on variational principles and the concept of reference space has been successfully developed earlier and reported in [4]. At the Øystese workshop, we demonstrated that this grid-generation method is effective in handling steep and multivalued free-surface boundaries and also in providing means to control grid properties such as coordinate spacings and cell-area distribution [5]. The applications in [5] were for inviscid-fluid problems.

The computations for a viscous fluid proceed differently. The auxiliary velocity field is computed using the momentum equations initially with the pressure-gradient term neglected. A Poisson equation is solved to obtain the pressure field subject to the appropriate free-surface and body boundary conditions. Divergence-free velocity field is then computed from the auxiliary velocity field by taking into account the correctional effects of the pressure results. For the results presented in this work, first-order upwind scheme is used to treat the nonlinear convective terms of the momentum equation. Other spatial derivatives i the flow and grid equations are discretized to second order accuracy. The pressure Poisson